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14. ABSTRACT: The work reported here discusses two topics. First, the design and test of a GPS pattern reconfigurable antenna is reported. It is shown through computer simulations and measurements that the beamwidth of the antenna can be changed by turning diode switches on and off. This antenna concept was developed to minimize the effect of interfering signals incident on the antenna along the horizon. This work also shows that microstrip antennas can be fabricated with a thick substrate without the usual surface wave problem. The second topic reported here is the development of the theory of characteristic modes in the time domain. The method described here uses the FDTD technique and has a major advantage over frequency domain algorithms because the resonances of the structure can be captured in a single FDTD run. Examples are given where resonance frequencies as well as characteristic modes are found for several structures, including a printed dipole, a reconfigurable printed antenna and a log-periodic antenna. To validate the proposed method, simulated results and analytical solutions are compared and shown to have excellent agreement.					
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Multilayer Reconfigurable GPS Antennas and Platform Effects

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1. Objectives

The main goal of this study was to develop and implement novel concepts for reconfigurable printed antennas. Although there are a variety of reconfigurable antenna concepts (frequency, polarization, input impedance), we have been concentrating on pattern reconfigurable antennas. An immediate application of the concepts being developed here are for the global positioning system (GPS). The antennas being considered here can potentially be used in airborne systems where jamming signal generated on the ground are incident on the antenna. The systematic design of this class of antennas requires novel design and analysis techniques to avoid brute force methods. Therefore, a secondary goal of this study was to develop and implement alternative techniques for the design of reconfigurable antennas. Owing to its advantage for providing a clear physical insight to the behavior of antennas, the theory of Characteristic Modes (CM) has been developed in the time domain instead of the frequency domain. The conventional approach for computing the characteristic modes of an antenna has been in the frequency domain using the Method of Moments. The calculation of the resonances of the structure is nevertheless considerably time consuming because it is necessary to sweep the frequency and observe the eigenvalue for each current mode. An alternative method for computing the characteristic modes is proposed here using the finite difference time domain (FDTD) technique. The proposed method provides a major advantage over conventional frequency domain algorithms because the resonances of the structure can be captured in a single FDTD run. In this report, resonance frequencies as well as the characteristic modes themselves are computed using the proposed method. CM analysis can be used to understand the behavior of radiation patterns, antenna scattering and input impedance. It is also very useful in pattern synthesis.

2. Status of Effort

Two main tasks have been completed under this effort. The first one is the design of a pattern reconfigurable antenna while the second involves the development of a time-domain version of the method of CM.

- Under the support of this grant, Mr. Nuttawit Surittikul has completed his Ph.D. dissertation in March 2006. Part of his dissertation involved the development of a novel pattern reconfigurable printed antenna element for Global Positioning System (GPS) applications. A possible scenario where this antenna can be useful is depicted in Figure 1 where the beam of the GPS antenna can change its beamwidth in response to interfering signals incident mostly along the horizon. This scenario is typical for airborne GPS systems on UAVs..

This antenna element consists of a microstrip patch, fed by four probes, and surrounded by a parasitic octagonal metallic ring loaded with diode switches. Although two probes are sufficient to generate circular polarization (CP), four probes gives a much better pattern in terms of symmetry in the azimuthal plane. The main concepts developed for this antenna are as follows. The patch and ring are located on top of a thick dielectric substrate to generate strong surface waves. Most printed antennas are designed using thin substrates to minimize these waves. The novel concept developed here is based on controlling the propagation characteristics of surface waves within the substrate by

using a metallic parasitic ring. If properly designed, this ring can control the radiated surface waves that interact with the main beam radiated by the patch itself.

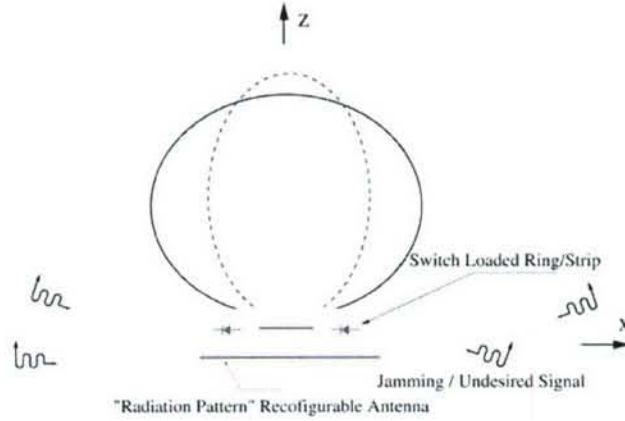


Figure 1: Scenario of radiation pattern of a reconfigurable antenna in the presence of unintentional interfering signals. These signals are assumed to be incident mostly along the horizon

To make the antenna reconfigurable, the parasitic ring was loaded with electronic switches; in this case, diodes. A very challenging design issue was the need for circuitry to bias the diodes. The mere presence of the circuitry distorted the radiation pattern. Accurate computer models were developed for all components of the antenna. Several prototype antennas were built based on this design concept. It was shown through computer simulations and measurements that the beamwidth of the antenna can be changed by turning the diode switches on and off. This concept will work properly if three components of the antenna work together, namely, the radiating patch, the diode switches and biasing circuitry. This effort also shows that microstrip antennas can be fabricated with a thick substrate without the usual surface wave problem.

- Characteristic current modes (CM), $\{J_n\}$, are defined as a set of real (or constant phase) surface currents on the surface of a conducting body or volumetric currents within a material body (usually dielectric). These currents depend only on the geometry and material properties of the antenna, but are independent of any specific source or excitation. Associated with each characteristic mode is a real characteristic value or eigenvalue, λ_n . The magnitude of the eigenvalue indicates how well that particular mode radiates. Modes with small $|\lambda_n|$ are good radiators, whereas those with large $|\lambda_n|$ are poor radiators. The closer the eigenvalue is to zero, and accordingly to resonance, the more significant is its contribution to the total radiation pattern. Relevant information about antennas resonant behavior can also be secured by examining the behavior of the eigenvalues with frequency. The conventional approach for computing the characteristic modes has been realized thus far only in the frequency domain. The calculation of the resonances is, nevertheless, considerably time consuming, as we need to sweep the frequency and observe the eigenvalue for each particular mode.

The new proposed method for computing the characteristic modes is implemented in the time domain using the FDTD technique. The three dimensional FDTD method is a

general and straight forward implementation of Maxwell's equations and provides a rigorous solution to a variety of electromagnetic wave problems. The major advantage of the proposed method is that wide-band spectral calculations are possible from just a single FDTD run. To calculate a spectral response, structures should be exposed to a very wide-band excitation. To do so, the initial conditions on the electric fields in the entire computational domain are generated with random numbers having a uniform distribution. This is equivalent to exciting the structure with a very wide-band signal. A top level flow chart of the proposed algorithm is shown in Figure 2.

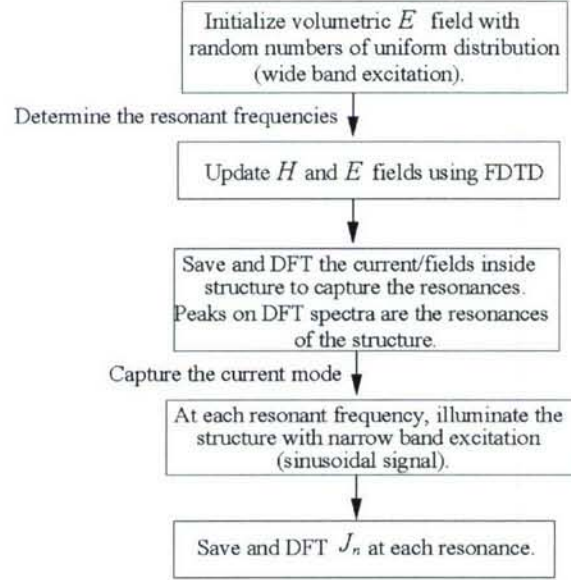


Figure 2: Proposed algorithm for calculating the characteristic modes. This novel scheme is performed in the time domain using the finite difference time domain (FDTD) technique

After initializing the domain (initial conditions), the fields are then updated using the well known time stepping FDTD algorithm. However, as time marches on, we record the waveforms, either the surface currents on the conducting bodies or the fields within the structure and simultaneously perform the DFT of these time dependent signals to obtain their frequency responses. The resonances of the structure are assumed to occur at the spectral peaks. Keeping in mind that it is not guaranteed that all the resonances of the structure will be captured from just a single FDTD run, several FDTD runs are performed with different seed numbers for random number generations to minimize the probability of missing some of the resonances. In addition, various observation or monitoring points are required to ensure that all the resonant modes are captured. In other words, it is possible that the time domain waveform could be sampled at a null of a particular mode, resulting in a weak DFT spectrum. It is worth noting that by combining these DFT spectra obtained from several monitoring points, "cleaner" spectral peaks can be obtained. Once the resonances are determined, the characteristic modes can be captured in two ways. They can be directly obtained from the original FDTD run initiated with the random initial conditions. However, it was found the modes to be somewhat contaminated with other modes. The scheme currently being used is based on the source

excitation technique. At each resonant frequency, the structure is illuminated with a narrow band signal such as sinusoidal with pulse envelope, i.e. a Gaussian pulse with a sinusoidal carrier at center frequency of interest. These narrow band signals are intentionally chosen to compute fields and/or currents at one particular frequency. It is worth noting that it is important to illuminate the structure with a narrow band signal in every polarization and from multiple directions to ensure that the characteristic mode is completely and correctly captured.

3. Accomplishments

In this section specific examples of the work accomplished on the two tasks mentioned above will be given. The first set of examples will concentrate on the design, simulation, implementation and testing of a GPS reconfigurable antenna. The second set of examples deals with the application of the CM technique to the design of antennas.

- **Reconfigurable Antennas**

As discussed at the introduction, reconfigurable antennas have the ability to modify their radiation characteristics such as radiation pattern, frequency of operation, polarization or even a combination of these features in real time. The antenna considered here and shown in Figure 3 is a microstrip patch antenna that radiates a broad beam in the upper hemisphere so it can receive GPS signals from satellites as depicted in Figure 1.

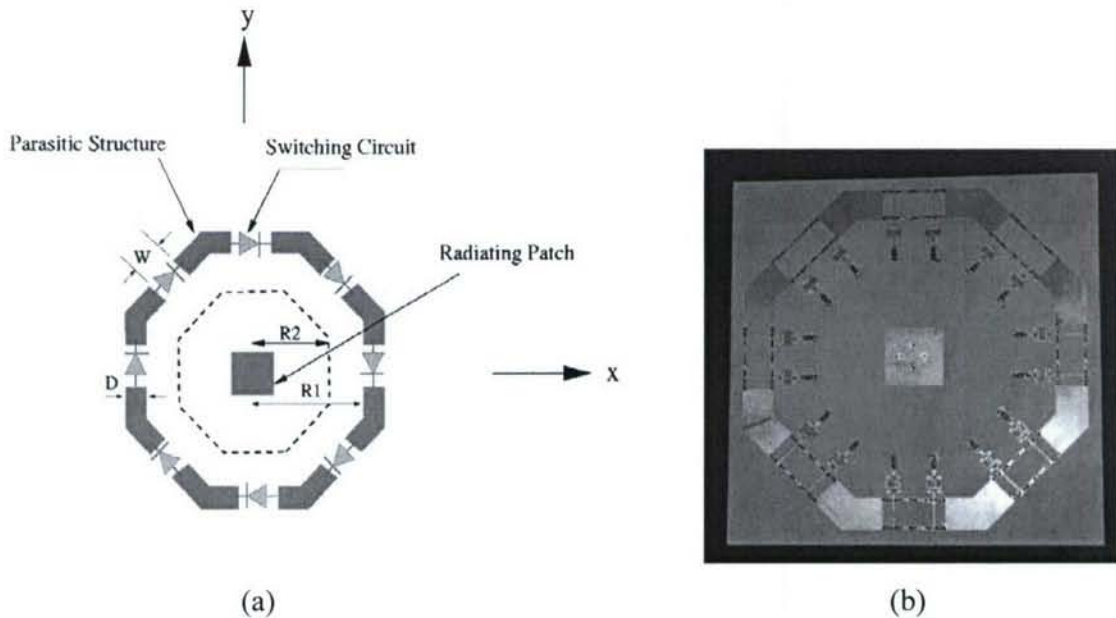


Figure 3: Geometry of the proposed reconfigurable antenna: (a) Schematic of a patch surrounded by a parasitic ring (b) Picture of the actual antenna consisting of a square patch surrounded by the switch-loaded octagonal metallic ring. The radiating element is mounted on the thick substrate ($\sim 0.12 \lambda_d$) which is used for surface wave excitation

The application also assumes the presence of interfering signals, which arrive at the antenna from directions approximately $(+10^\circ \text{ to } -15^\circ)$ from the horizon. This is a common scenario for antennas on airborne platforms. As a result, the main objective is to design the antenna capable of reconfiguring its radiation pattern during real time operation such that it maintains its broad pattern in the absence of interferences, and is capable of narrowing its pattern beamwidth when interfering signals arrive.

To implement the four probe feeding technique, a two-stage Wilkinson power divider was designed and built. This passive device generates four signals with a progressive 90° phase shift as illustrated in Figure 4. The actual implementation of the device for operation at L1 is shown in Figure 5 where both front and back view are depicted.

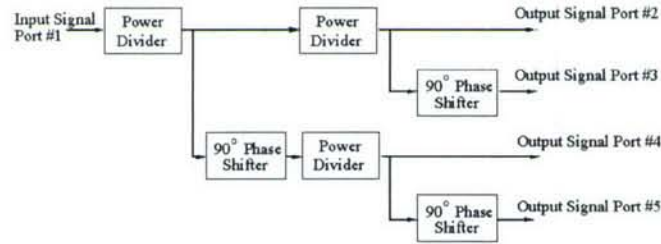
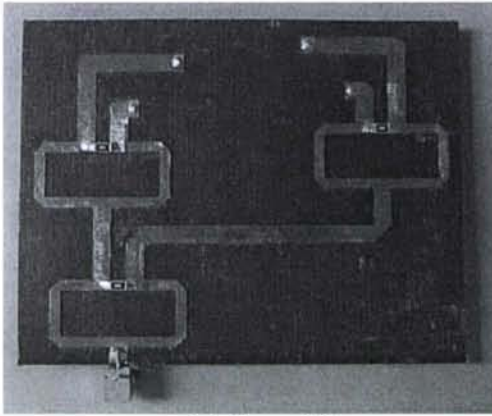
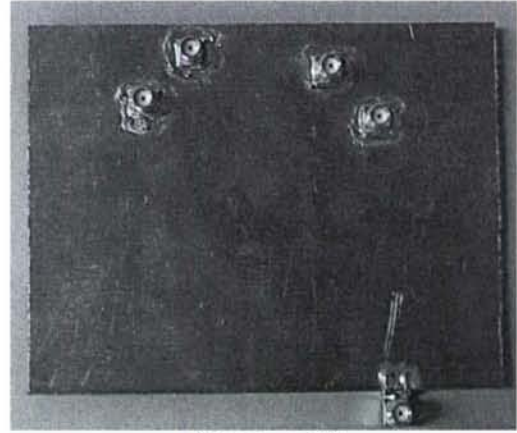


Figure 4: Schematic of a two-stage Wilkinson power divider



(a) Front View



(b) Back View

Figure 5: Implemented two-stage Wilkinson power divider. The substrate (RT/Duroid 5870, thickness=1.575 mm) dimensions are 125 mm x 65 mm

The performance of the power divider is crucial since it generates the RHCP signal. The measured magnitudes of S_{21} , S_{31} , S_{41} and S_{51} across the band of interest are depicted in Figure 6(a). Clearly, they remain fairly constant across the entire band with the maximum deviation (between the ports) of 0.2 dB at 1.575 GHz. In addition, Figure 6(b) shows the measured phase response over the same frequency band. As shown, the relative phase increment at 1.575 GHz is 0° , 89.7° , 185.3° and 275.3° respectively. Thus, it is shown that a high quality circularly polarized pattern can be achieved using this feed network. It is also worth noting

that the coupling between these output ports (i.e. S_{23} , S_{24} , etc.) is very insignificant, approximately -35 dB.

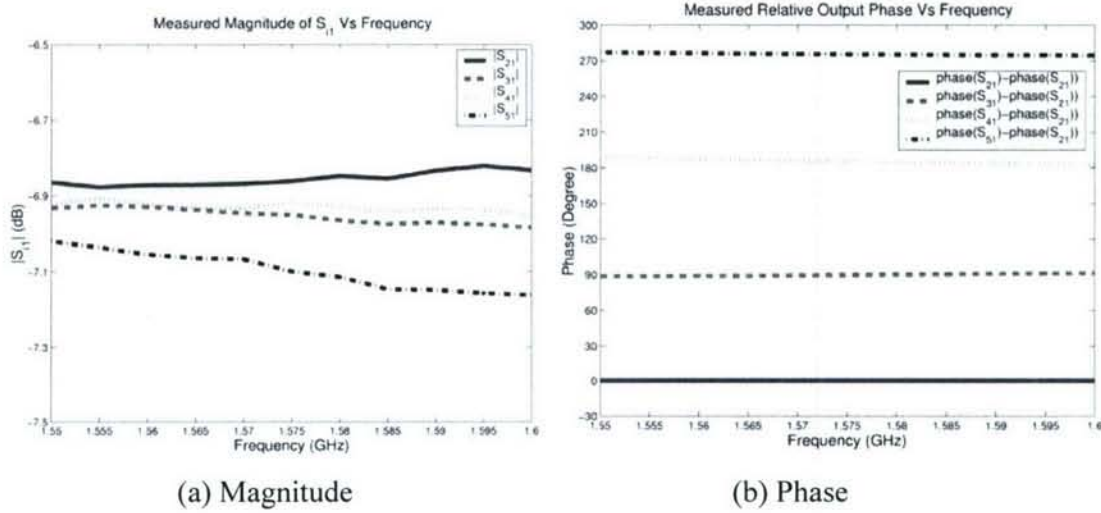


Figure 6: Measured frequency response of the two-stage Wilkinson power divider

Figure 7 shows a comparison of the measured elevation gain pattern for the horizontal component (G_ϕ) for the on and off states of the switches at $\phi = 0^\circ$, 15° , 45° and 90° . As expected, the measured gain patterns are very similar to the simulated results. It can be seen that the measured gain patterns are fairly symmetric on azimuth. Moreover, the measured gain patterns when the switches are *off* are consistently lower at every elevation plane than those when the switches are *on*. The small oscillations of the gain patterns probably arise from the fields scattered by the coaxial cables connecting the antenna and the feeding circuit during the measurement process. Figure 8(a) shows the measured right handed circular polarized (RHCP) gain pattern for the *on* and *off* states of the switches at $\phi = 0^\circ$, 15° , 45° and 90° . As illustrated, the measured RHCP gain patterns are fairly symmetric on azimuth. Moreover, the measured RHCP gain patterns when the switches are *off* are consistently lower than those when the switches are *on*, especially in the directions along the horizon. As a result, it can be seen that the antenna can be used not only to minimize those jamming signals, but also to reduce the multi-path signals. These patterns also show that the GPS antenna performs well in terms of receiving signals from satellites for both cases, namely, when the switches are *on* or *off*. Finally, Figure 8(b) illustrates the measured axial ratio for the *on* and *off* states of the switches at $\phi = 0^\circ$, 15° , 45° and 90° . It is noted that when switches are activated, the antenna still has an excellent axial ratio that is less than 4 dB for θ between 0° and 90° in all planes, ($\phi = 0^\circ$, 15° , 45° , 90°). On the other hand, the axial ratio of the switches *off* cases is below 3 dB for θ between 0° and 35° . It is clear that the axial ratio is dependent on the operating states of the switches; however, it remains very good down to 35° in elevation.

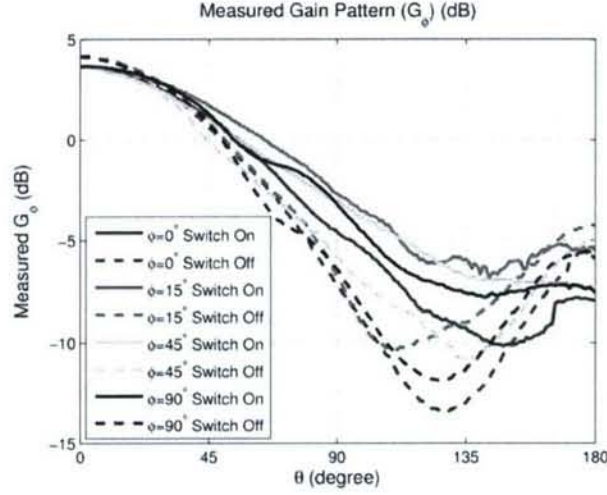


Figure 7: Measured gain patterns (G_ϕ) for the *on* and *off* states of the switches for $\phi = 0^\circ, \phi = 15^\circ, \phi = 45^\circ$ and $\phi = 90^\circ$

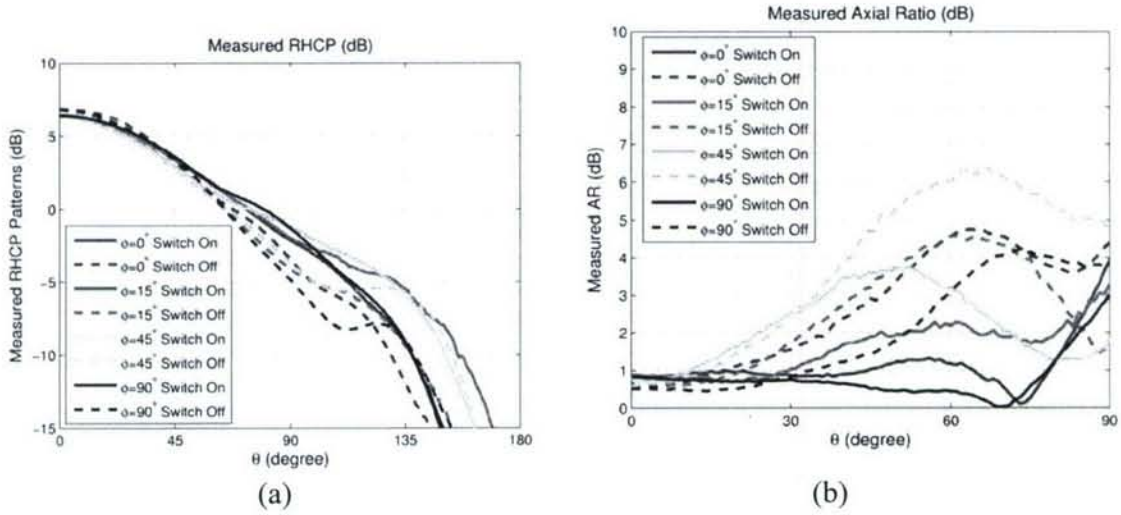


Figure 8: Measured (a) RHCP gain patterns (G_{RHCP}) and (b) Axial Ratio for the *on* and *off* states of the switches for $\phi = 0^\circ, \phi = 15^\circ, \phi = 45^\circ$ and $\phi = 90^\circ$

• Application of CM techniques to Antenna Design

Before the CM time domain method developed by the authors is applied to antenna problems, it is important to assess its accuracy. Although several cases were considered, one simple well known problem is a metallic rectangular waveguide. This case was chosen because closed form solutions are known for the resonant frequencies of all the modes. Table 1 summarizes and compares the analytical results with the CM-based results for ten TM modes. It can be observed that the CM-based results are very close to the closed form

solutions. This demonstrates the accuracy of the CM-base method in computing the resonant frequencies.

Resonant Modes	$T M_{11}$	$T M_{21}$	$T M_{31}$	$T M_{12}$	$T M_{22}$
Analytical Solution (GHz)	3.351	4.239	5.404	6.180	6.703
Proposed Method (GHz)	3.364	4.253	5.418	6.194	6.711

Resonant Modes	$T M_{32}$	$T M_{51}$	$T M_{42}$	$T M_{13}$	$T M_{23}$
Analytical Solution (GHz)	7.494	8.072	8.479	9.117	9.480
Proposed Method (GHz)	7.504	8.086	8.491	9.121	9.493

Table 1: Comparison of the resonances of a rectangular waveguide obtained from analytical solutions and the proposed method

Another well known antenna is the printed dipole as shown in Figure 9. It consists of two collinear thin wires each about quarter of a wavelength long. The DFT spectra of the current induced on the printed dipole is captured and shown in Figure 10.

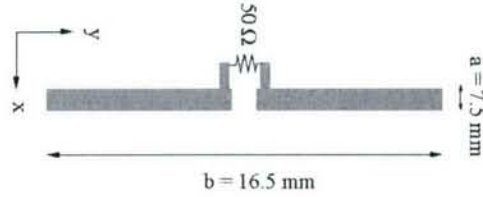


Figure 9: Geometry of a printed dipole antenna

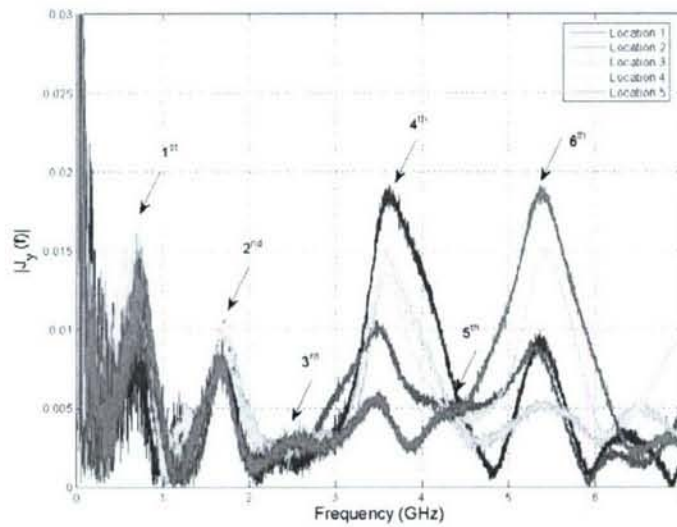


Figure 10: Frequency spectra of the induced currents on the printed dipole

The calculated resonances match very well with the approximate analytical ones, i.e.; $f_{res}(n) \cong n\Delta f$ where Δf is the first resonance of the dipole, ≈ 0.82 GHz in this case and $n=1, 2, 3 \dots$. As is well known, this analytical formulation is approximate and is based on the assumption that the dipole is very thin compared to the wavelength. The various resonance curves in Figure 10 are obtained by sampling the fields at different locations along the dipole. This is done to assure that no mode is sampled with one single point at its null. If this were the case, that particular mode would not be detected.

The next antenna analyzed with the CM time domain method is the GPS reconfigurable antenna discussed above. For the particular application under consideration, the control of the surface waves is crucial to achieve pattern reconfigurability. Our proposed reconfigurable scheme is based on the modification of the EM propagation characteristics of the surface waves, and thus the radiation pattern, through the use of a metallic switch-loaded parasitic structure such that the radiated surface waves contribute to the main beam pattern in a controlled fashion. The switches provide two different ring configurations and pattern reconfigurability is controlled by the two operating states of the switches (on/off)

The antenna considered here was designed for the L1 GPS frequency, namely, 1.575 GHz. Although two concepts for controlling both vertical and horizontal field components, i.e. E_θ and E_ϕ respectively, are discussed in our previous reports and conference papers, the work presented in this report considers a scheme to modify the beamwidth of the horizontal field component, E_ϕ while the E_θ component remains mostly unchanged due to the geometry of the parasitic structure. The basic antenna geometry is shown in Figure 3. It consists of a square radiating patch of size, 27.50 mm, mounted on a dielectric substrate of relative permittivity (dielectric constant) equal to 9.2. The dielectric substrate is 177.80 mm by 177.80 mm with thickness of 7.62 mm ($0.1213 \lambda_d$). The radiating patch is surrounded by a switch loaded octagonal ring. As mentioned previously, a thick substrate was specifically chosen in order to excite surface waves. Control of the surface waves is implemented using a switch loaded octagonal ring. For purposes of controlling the horizontal field component, E_ϕ , a thin ring is used so the longitudinal induced currents are dominant while the transverse currents are weak. Furthermore, the ground plane of the antenna is smaller than the substrate and ring and it is also octagonal in shape to maintain a symmetric pattern in azimuth.

Using simple models for the switches the following dimensions were obtained for the parasitic ring and ground plane: $W = 22$ mm, $R_1 = 75.625$ mm, $D = 6.875$ mm and $R_2 = 23.375$ mm. A FDTD-based computer code, developed by the authors, was used for this purpose. The grid sizes, i.e. d_x , d_y , and d_z , are approximately one-twentieth of a wavelength at the frequency of operation, 1.575 GHz. In addition, a curved PEC section is modeled with both a staircase model and a diagonal split-cell model. The simulated results, such as radiation pattern and input impedance, obtained from both methods are almost identical because the grid size is electrically small that even the staircase model can be used to accurately model any curved section in this problem.

To apply the CM method, let us consider the surface currents induced on the parasitic ring. By using the method of characteristic modes, the eigencurrents and their corresponding resonant frequencies can be determined. Figure 11 shows the frequency spectra of the currents (obtained with a DFT) on the ring for the two operating states of the switches (*on* and *off*). Figure 11(a) represents the DFT current spectra on the ring when the switches are *on*. As can be observed, numerous current modes are induced at approximately 0.4 GHz intervals, similar to the resonances attained for a loop antenna. At the L1 band, the radiation pattern of the ring when the switches are *on* will mainly come from contributions from the forth and fifth current modes. These two current modes have resonant frequencies closest to the operating frequency (L1 band) and thus have the smallest eigenvalues among the induced current modes. Recall that the smaller the eigenvalue, the stronger the contribution of the mode. On the other hand, Figure 11(b) shows the DFT current spectra on the ring when all switches are turned *off*. It is clear from the figure that the resonant frequencies of the modes are changed when the switches are *off*. The mode with its resonant frequency closest to L1 is the third mode with a resonant frequency of 1.598 GHz. As a result, the radiation pattern obtained from the ring (with switches *off*) is mostly due to the third current mode. This statement can be validated by comparing the total radiation pattern of the ring at 1.575 GHz to the pattern radiated by the third current mode.

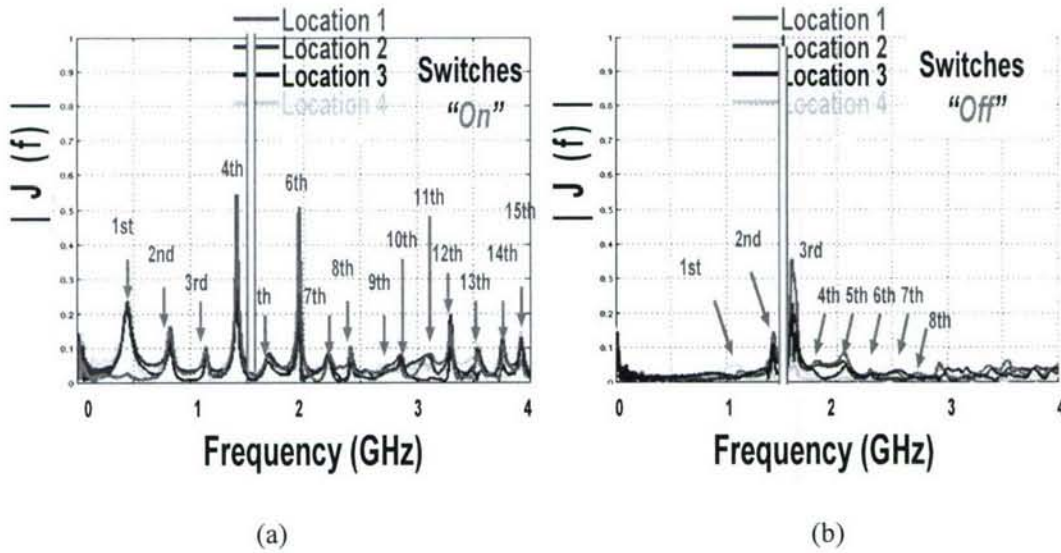


Figure 11: Frequency spectra of the current modes induced on the octagonal ring: (a) Switches are *on* (b): Switches are *off*

Figure 12 depicts the first, forth and fifth characteristic modes as well as their corresponding radiation patterns. It turn out that the horizontal field component E_ϕ radiated by the ring when the switches are turned *on* is almost identical to the eigenpatterns radiated from the forth and fifth modes, but very distinct from the eigenpattern of the first mode. As a result, the field radiated from the ring (switches *on*) at the L1 band is primarily due to contributions from the forth and fifth mode. Similarly, Figure 12 also describes the second and third characteristic modes along with their eigenpatterns when the switches are *off*. It is also clear

that the horizontal field component (E_ϕ) radiated by the ring when the switches are turned *off* is very similar to the eigenpattern radiated by the third mode. In other words, the total field radiated by the ring (switches are *off*) at the L1 band is mostly due to the third mode.

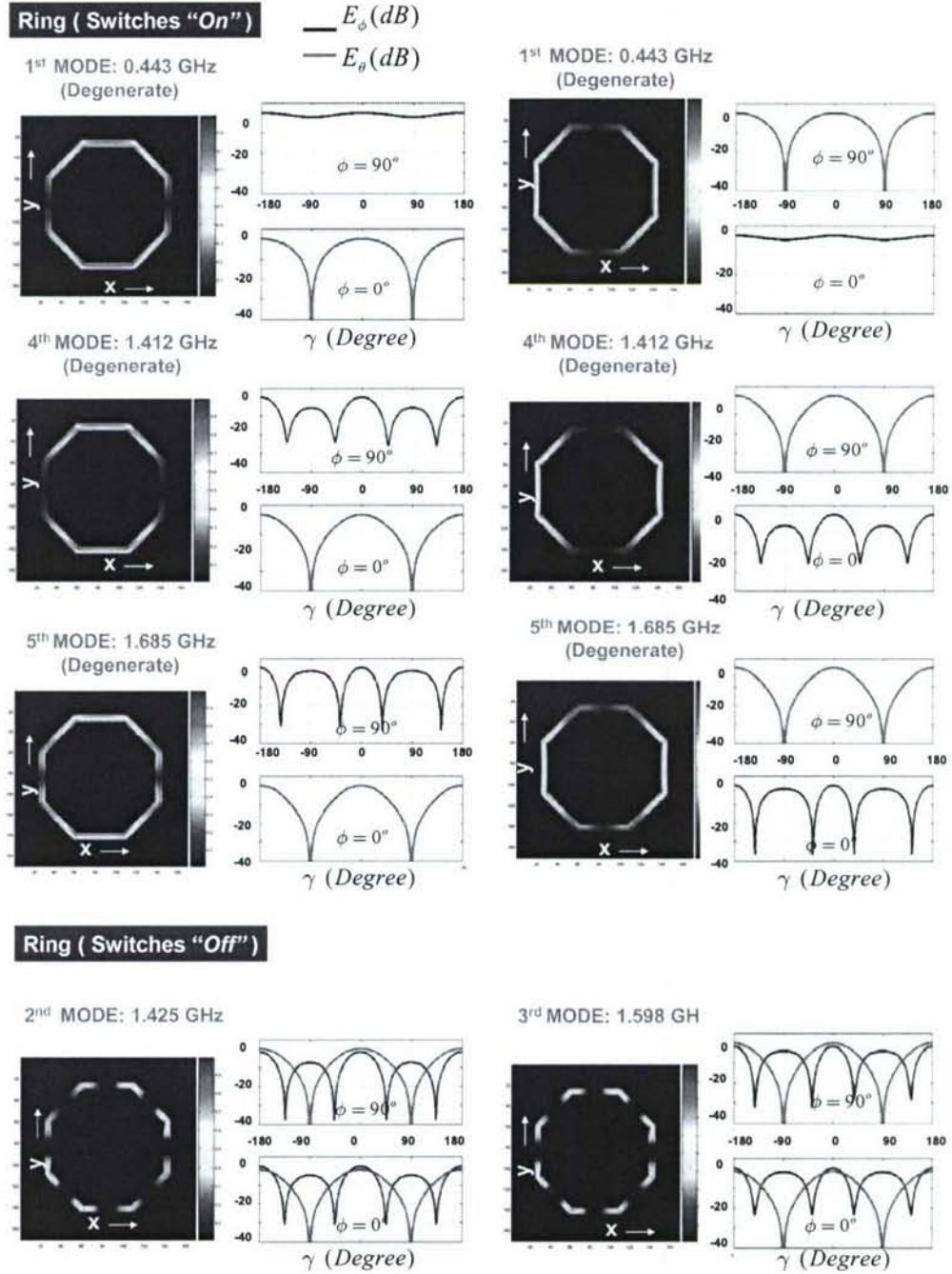


Figure 12: The characteristic modes and their corresponding eigenpatterns of the parasitic ring when the switches are turned *on* and *off*.

The information obtained with the proposed method could be very useful in the analysis of the reconfigurable antennas as it provides more physical insight into the behavior of the currents induced on the ring. Furthermore, this information could also be used in the antenna design cycle, such as the fine tuning process. For example, the width of the cuts could be readjusted such that the induced current of the ring resonates exactly at the L1 band, resulting in a stronger contribution from the third current mode. Although not shown here, the reconfigurability could be increased from 7-8 dB as shown in the current example to approximate 9-10 dB.

One of the major drawbacks with many antennas is that they have a relatively small bandwidth. This is particularly true of resonant antennas, such as dipole and microstrip antennas. However, there are other classes of antennas, such as log periodic antennas, which provide reasonable gain levels while being able to operate over a wide frequency bandwidth. The log-periodic antenna is a broadband, multi-element, unidirectional, narrow-beam antenna having structural geometry such that its impedance and radiation characteristics repeat periodically as the logarithm of frequency. In practice, the impedance and/or radiation pattern variations over the frequency band of operation are minor, and log-periodic antennas are usually considered to be frequency independent antennas. The length and spacing of the elements of the log-periodic antenna increase logarithmically from one end to the other. The log periodic antenna can exist in a number of forms. One well known antenna is the log-periodic toothed planar antenna shown in Figure 13. It is similar to the bow-tie antenna except for the teeth. The teeth act to disturb the currents that would flow if the antenna were a bow-tie type radiator. Work on log-periodic antennas is extensive and can be readily found in the literature.

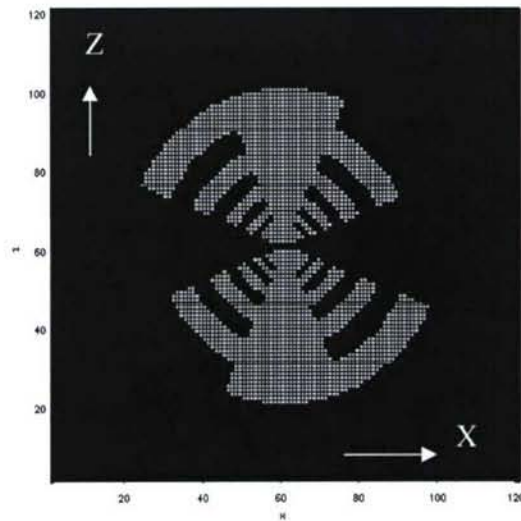


Figure 13: Geometry of a log-periodic antenna.

Figure 14 shows a DFT current spectra (x and z polarizations) induced on the log-periodic antenna. It is clear that the antenna resonates in a logarithmic periodic fashion. The first three eigencurrents as well as their corresponding eigenpatterns are presented in Figure 15.

The patterns look almost identical for the vertical field component (E_θ), which is one of the characteristics of the frequency independent antenna.

The initial design of log-periodic antennas is usually done using simple approximate design formulas. Although the method predicts reasonably accurate resonances, it is sometimes unable to determine the actual antenna resonances due to the complicated antenna geometry. The next step is to model the antenna with more accurate numerical techniques. Although there are a variety of such methods, they don't provide much physical insight. The Method of Characteristic Modes can play a crucial role because it can calculate all the natural modes of the antenna, their resonant frequencies, radiated fields of each mode as well as the Q and bandwidth. This information can provide value insight into the behavior of the antenna. Knowing the natural modes can also be very helpful in the fine tuning of the antenna and the design of the feeding network.

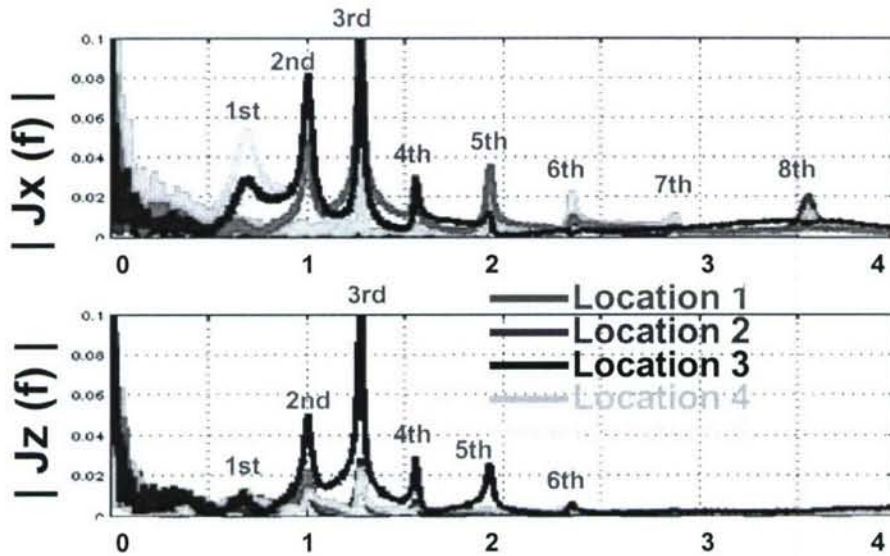
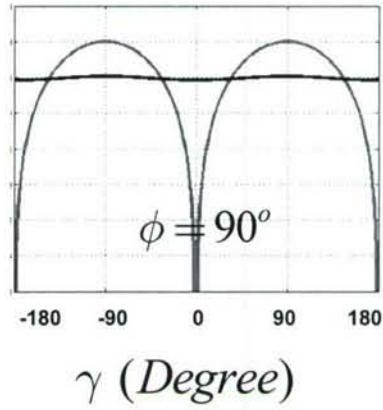
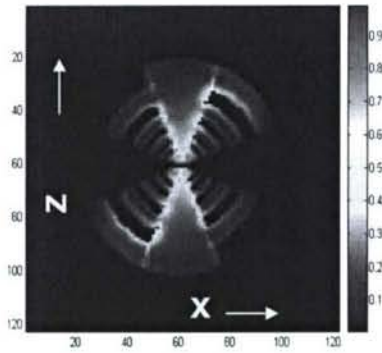


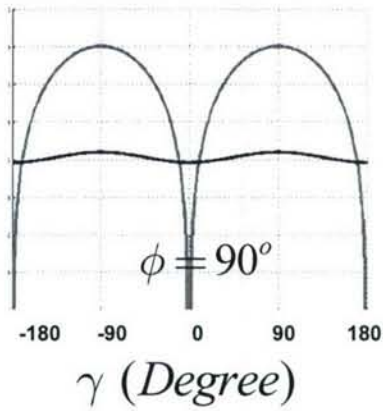
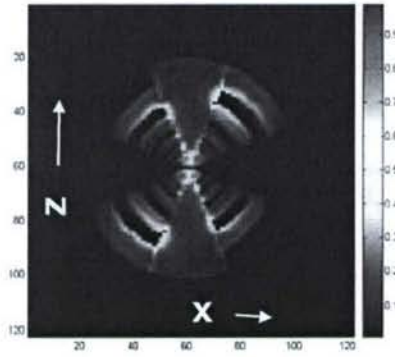
Figure 14: Frequency spectra of the current modes induced on the log-periodic antenna.

As demonstrated by these examples, the method of CM in the time domain is a very useful tool for analyzing and designing antennas and other scattering structures. It provides physical insight into the behavior of the structure and can be used in conjunction with other design tools. In contrast to most CAD-based packages, the CM method provides information about the behavior of the structure and can allow the control of the currents and radiated fields. The main reason for the advantage of this tool is that it allows us to determine the natural modes that exist in a particular structure as well as the resonance frequencies of these modes.

1st EIGEN MODE: 0.685 GHz



2nd EIGEN MODE: 1.000 GHz — E_θ (dB) — E_ϕ (dB)



3rd EIGEN MODE: 1.275 GHz

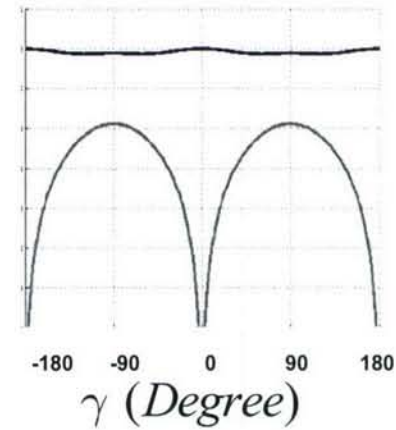
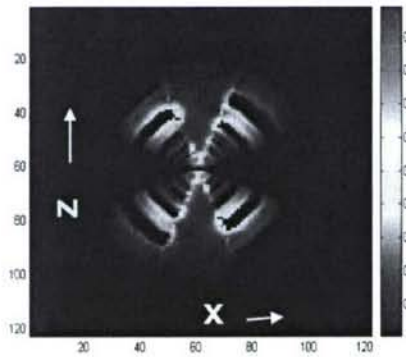


Figure 15: The eigencurrents on the log periodic antenna and their corresponding radiated eigenfields.

4. Personnel Supported

- Prof. Roberto Rojas, PI.
- Nuttawit Surittikul, Graduate Student (50% until March 2005). Graduated with a PhD degree in March 2006.

5. Technical Publications

1. Journal Publications

- K. W. Lee, R.G. Rojas and N. Surittikul, "A Pattern Reconfigurable Microstrip Antenna Element," *Microwave and Optical Technology Letters*, Volume 48, Issue 6, pp. 1117-1119, June 2006,
- N. Surittikul, S. Iyer and R.G. Rojas, "Pattern Reconfigurable Printed Antenna for GPS Applications," submitted to *IEEE Trans. Antennas & Propagation*

2. Reviewed Conference Proceedings

- N. Surittikul and R.G. Rojas, "Time Domain Method to compute Quality Factors and Bandwidths of characteristic modes of antennas, *IEEE AP-S International Symposium, USNC/URSI National Radio Science Meetings and AMEREM Meeting*, Albuquerque, NM, July 9-14, 2006
- N. Surittikul and R.G. Rojas, "Time Domain Method of Characteristic Modes for the Analysis/Design of Antennas," *2005 IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting*, Washington DC, July 3-8, 2005
- N. Surittikul and R.G. Rojas, "Analysis of Reconfigurable Printed Antennas using Characteristic Modes: FDTD Approach," *IEEE AP-S International Symposium and USNC/URSI National Radio Science Meetings, Monterey, CA*, June 20-25, 2004
- N. Surittikul and R.G. Rojas and K.W. Lee, "Reconfigurable Circularly Polarized Dual Band Stacked Microstrip Antenna," *IEEE AP-S International Symposium and USNC/URSI National Radio Science Meetings*, Columbus, OH, June 22-27, 2003

3. Journal Papers in Preparation:

- N. Surittikul and R. G. Rojas, "Analysis of Reconfigurable Printed Antenna using Theory of Characteristic Modes: FDTD Approach," to be submitted to *IEEE Transactions on Antennas and Propagation*.
- N. Surittikul, S. Iyer and R. G. Rojas, "Dual Band Reconfigurable Stacked Microstrip Antenna for GPS Applications," to be submitted to *IEEE Transactions on Antennas and Propagation*.

6. Interactions/Transitions

- Mr. Kevin Sickles at the AFRL/SNRR, Wright Patterson Air Force Base, has supported our work in the past with a graduate student. We are now working on the design of ultra wideband antennas conformal to small UAVs. There is a great need by the Air Force to have antennas conformal to small UAVs capable of operating down to 30 MHz in frequency. The reconfigurable antenna concepts as

well as the method of characteristic modes (based on the FDTD) developed under this funding is being used in the work dealing with electrically small conformal antennas. Note that our partner in this work is a UAV manufacturer (L3-Geneva). There are plans to design, test and eventually fly this antenna on a small UAV.

- Mr. James Tuss at the AFRL Wright Patterson Air Force Base, in conjunction with Mr. Sickles, are supporting our work on large bandwidth antennas conformal to small UAVs.
- We are also involved with SI2, a small company located in Massachusetts. This company has developed "direct write" technology to print antennas and microwave circuits directly on conformal structures. We have designed for them a ring for a GPS antenna mounted on the dome of the Predator UAV. This ring was designed to improve the front-to-back ratio of the antenna.

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7. **Patent Disclosures**

None

8. **Honors**

None